

## Towards An Integrated Optical Transient Utility

S. R. KULKARNI<sup>1</sup>

<sup>1</sup>*Astronomy & Astrophysics 249-17  
California Institute of Technology  
Pasadena, CA 91108, USA*

### ABSTRACT

The ongoing optical time-domain astronomy surveys are routinely reporting fifty transient candidates per night. Here, I investigate the demographics of astronomical transients and supernova classifications reported to the Transient Name Server in the year 2019. I find that only a tenth of the transients were spectrally classified. This severe “bottleneck” problem should concern astronomers and also funding agencies, especially LSST will make the situation worse by a factor of 20 (or more). We need to fundamentally rethink the purpose of surveys for transients. Here, after undertaking a detailed investigation of this issue I offer some solutions. Going forward, astronomers will employ two different methodologies: (1) multi-band photometric method which is well suited to the study of very large, many tens of thousands, samples of faint transients; (2) spectral classifications of thousands of bright transients found in shallow and nightly cadenced wide-field photometry surveys and transients associated with galaxies in the local Universe. The latter program, in addition to unearthing new types of transients and offering astronomers opportunities to undertake extensive follow up of interesting transients, is needed to set the stage for the former. Specifically, I suggest a globally coordinated effort to spectrally classify a complete sample of bright supernovae ( $\lesssim 19.5$  mag) and transients within the local Universe ( $< 200$  Mpc). The proposed program is within reach – thanks to the on-going wide-field surveys, the development of novel spectrographs tuned for classification, great improvements in throughput of spectrographs and the increasing availability of robotic telescopes.

*Keywords:* instrumentation: photometric and spectrographs — surveys — supernovae: general — catalogs

### 1. BACKGROUND

Time domain astronomy at optical bands is one of the oldest areas of study in astronomy. At the beginning of the last century the focus was the study of variable objects (e.g., RR Lyrae, Cepheid variables) and novae. These studies led to revolutionary findings of a much bigger Galaxy and a larger Universe than had been considered.

In 1936, using an 18-inch Schmidt-type telescope at Palomar, then a novel type of telescope, Fritz Zwicky started a systematic program to study supernovae (SNe). Two years earlier Baade & Zwicky had already concluded that SNe marked the end states of stars. In that spirit, going forward, I will use the term “transient”

exclusively for events which happen only once. This definition automatically excludes eruptive variables such as dwarf novae and supernova imposters.

By the end of the last century the study of SNe at optical wavelengths, primarily motivated by the potential use of SNe as extragalactic yardsticks, had become a major area of astronomy. The latter culminated with the discovery, through the light curves of SNe of type Ia and the redshifts of the host galaxies, of the accelerated expansion of the Universe. The systematic study of cosmological SNe is one of the principal goals of the upcoming Vera C. Rubin Observatory<sup>1</sup> and the Wide-field Infrared Survey Telescope (WFIRST) space mission.

Zwicky (1974) provides a very readable summary of supernova searches, starting from the Palomar 18-inch

Corresponding author: S. R. Kulkarni  
srk@astro.caltech.edu

<sup>1</sup> The principal survey that the Rubin Observatory will carry out is the Legacy Survey of Space and Time Survey or LSST.

program and going through the sixties (and including the Palomar 48-inch Schmidt-camera telescope now renamed as the Oschin Telescope). Early attempts at moving away from the photographic plate and manually operated telescopes are summarized by Colgate et al. (1975). In my view, any serious student of SN searches should read these two classic papers. Many of the ideas mentioned in these two papers are still valid today.

At the end of the last century, the Lick Observatory Supernova Survey (LOSS) ushered in the era of dedicated remote and subsequently robotic SN searches (Filippenko et al. 2001). LOSS targeted bright galaxies in the local Universe and, at its peak, was discovering about one hundred SNe per year. R. Quimby, for his thesis, used a 45-cm telescope with the then large field-of-view of  $3.4 \text{ deg}^2$  to search for SNe towards clusters of galaxies and found the first two members of a new class of extragalactic transients – super-luminous supernovae (Quimby 2006). The All Sky Automated Survey-Supernova survey (ASAS-SN; Shappee et al. 2014), initiated circa 2012, continued the tradition of looking for bright SNe but by undertaking a systematic search of the entire night sky (“blind” or “un-targeted” searches). For these three projects, the discovery rate was modest enough (few hundred per year) that members of the observing team visually inspected candidate events and announced highly reliable candidates. The candidates were bright enough ( $\lesssim 18 \text{ mag}$ ) that spectral classification of the candidates could be readily undertaken by the global SN community.

Separately, a number of wide-field surveys with CCD mosaics began, initially for specific purposes (e.g. searches for MACHOs, high redshift Ia supernovae, asteroids). One of the early general purpose CCD survey, the Palomar QUEST survey, was undertaken with the Palomar Oschin telescope (Djorgovski et al. 2008). It ran from 2003–2008 and was succeeded by the Palomar Transient Factory (PTF; Law et al. 2009). At about the same time, the Catalina Real-Time Sky Survey (CRTS; Drake et al. 2009), and PanSTARRS-1 (PS1; Tonry et al. 2012) came on line.

The SN rate shot up to thousands per year. For these surveys Machine Learning (ML) came in the nick of time (Bloom et al. 2012; Wright et al. 2015), as it lead to a substantial reduction in the load of visual inspection of candidates. These surveys marked the beginning of the era of “industrial” time domain surveys. At the present time, the major industrial surveys are Asteroid Terrestrial Impact Last Alert System (ATLAS; Tonry et al. 2018), PS1 and the Zwicky Transient Facility (ZTF; Bellm et al. 2019; the successor to PTF).

A major advance in the TDA field was the the development and immediate implementation of a novel imaging differencing algorithm (aka “ZOGY; Zackay et al. 2016). In this method, the recent image and the reference image are convolved with each other’s PSF and then subtracted. The resulting subtracted image, as one conclude based on the symmetry, will have far fewer imperfect subtractions. This method is not only optimal but also reduces the reliance on ML. Every clear night ZTF pumps out, in real time, hundreds of thousands of “alerts”<sup>2</sup> (Patterson et al. 2019).

The industrial surveys with their tremendous output of transient candidates have changed the landscape of the optical TDA field. The purpose of this paper is to quantitatively review this new landscape and identify new opportunities, especially bearing in mind the arrival of the Rubin Observatory.

The paper is organized as follows. The huge growth in the transient detection rate has led to a new clearing house for alerts which is summarized in §2. The increase in the transient detection rate has not been accompanied by corresponding increase in spectral classification. In fact, most of the transient candidates “die on the floor”. Stated bluntly, transient object astronomy field has already undergone a profound shift – from a relatively event-poor field to an event-drowning field. In view of this fundamental change in §3 I try to understand what constitutes meaningful discovery in the field optical transients. In §4 I present a quantitative analysis of “Astronomical Transients” (ATs) and SNe reported to the Transient Name Server (TNS)<sup>3</sup> in the year 2019. The bottleneck factor – the ratio of reported ATs to spectrally classified transients – now stands at 10. This factor is expected to increase over time. This bottleneck notwithstanding, I revisit the fundamental importance of spectral classification and determination of redshifts of transient events (§5). In §6 I suggest an integrated “Optical Transient Utility” consisting of an imaging element and spectral classification element. The two elements together provide, routinely, nightly cadenced light curves of the sky accompanied by spectral classification of all bright transients. In §7, I summarize the principal conclusions and then follow it up with some observations on the importance of clearing houses and astrophysics.

<sup>2</sup> In the parlance of modern time domain astronomy, an alert is a  $n\text{-}\sigma$  change in RA, DEC or flux. Taking the lead from LSST, the ZTF team has elected to use  $n = 5$ .

<sup>3</sup> <https://wis-tns.weizmann.ac.il/>

## 2. DISSEMINATION IN THE ERA OF INDUSTRIAL SURVEYS

Even a decade ago it was customary to announce SN discoveries via the Central Bureau for Astronomical Notifications (CBAT).<sup>4</sup> Astronomers sent reports to an editor and the editor assigned a SN name (e.g., SN 1987A). The standard medium for dissemination was telegrams of yore, later replaced by elegantly laid out post cards and most recently expressed through “electronic telegrams”.

Noting the rapid changes in the SN field in 2009 (§1 Gal-Yam et al. (2013) reviewed the operational side (detection rate, modes of reporting, classifications) of the SN field for the year 2010 and 2011. In 2009 the number of classifications was slightly behind the number of candidates. However, they found that over the next two years the discrepancy increased. Separately, the number of SNe (by which I mean transients with secure spectral classification) started to rise: 538 SNe in 2010 to 926 SNe in 2011. The reporting mechanism became chaotic with some observers reporting to the CBAT, some to Astronomer’s Telegram<sup>5</sup> (ATEL) and others via their own project pages.

The explosive growth in the detection rate of transients and the chaotic reporting led the International Astronomical Union (IAU) to call upon the community to create a single entity to receive reports of transients and assign them official IAU names. The result was the Transient Name Server (TNS, introduced in the previous section) which is run by a group of public spirited astronomers at the Weizmann Institute of Science, Israel. The transition from CBAT to TNS took place on 1 January 2016.

It is now the standard practice that astronomers routinely report (hopefully high fidelity) transient candidates to TNS and in return get “Astronomical Transient” (AT) designations for their candidates. The ATs are indexed in the same way as SN (e.g., AT 2019A, AT 2019B,..., AT 2019Z, AT 2019aa, AT 2019ab,...).

## 3. THE DISCOVERY PROCESS

We use the word “discovery” routinely. However, it is a potent word and it is worth dissecting the intended meaning of this word. In this section, I first discuss the field of GRBs as a case study and then follow it up summarizing the current discovery process for supernovae.

### 3.1. GRBs: A Case Study

GRBs have distinct high energy temporal and spectral signatures. It is relatively easy to reject false positives such as flares from the Sun or gamma-rays from lightning. In fact, the gamma-ray spectral and temporal data are sufficient, in most cases, to classify sub-types (short-hard, long-soft, repeater, tidal disruption events) within the family of gamma-ray transients. Next, the total annual rate of GRBs is modest, no more than a thousand per year.

The first detections of flashes of gamma-rays were made by Vela-3 and Vela-4 satellites in 1967. However, evidence that these are not artifacts nor of local origin (Earth, Sun) came only with triangulation offered by a constellation of Vela satellites (5A, 5B, 6A and 6B) circling the earth (Klebesadel et al. 1973). It is at this point one could say that extra-solar gamma-ray bursts were discovered. Over the next thirty years progress was stymied by poor localization and so the main focus was on statistical studies (e.g., logn-logs and distribution on the sky). The discovery of long-lived lower-energy emission radiation, aka the “afterglow” (Costa et al. 1997), revived the field. Thus, after 1997, what mattered the most was whether an afterglow was detected or not. In effect, the limiting step in GRB astronomy was set by the detection rate of afterglow emission.

The *Swift* Observatory<sup>6</sup> was explicitly built to detect X-ray and UV/optical afterglow. To this end, it employed a space-craft with high maneuverability. A wide-field coded-aperture mask imager detected bursts of hard X-rays with “crude” localization (arc minutes), following which the space-craft rapidly slewed so that “narrow” field-of-view but high sensitivity X-ray and optical/UV imagers could start detecting the afterglow. Armed with arc-second localization of the afterglow astronomers rush off to undertake multi-wavelength and, in particular, obtain the redshift via the afterglow (ideally) or that of the host galaxy (at a later time). It is this triplet of efforts that has enabled *Swift* to advance the GRB field.

In fact, a future general-purpose GRB missions will have to at least match *Swift*’s afterglow capabilities in order to get funded. Indeed, the planned Chinese-French Space Variable Objects Monitor (SVOM)<sup>7</sup> carries wide-field GRB detectors, narrow-field but sensitive X-ray and optical telescopes and, in addition, an ambitious array of dedicated ground-based optical telescopes (one for wide field imaging and 1-m telescopes with three-band imagers).

<sup>4</sup> <http://www.cbata.harvard.edu>

<sup>5</sup> <http://www.astronomerstelegram.org/>

<sup>6</sup> <https://swift.gsfc.nasa.gov/>. Now renamed as the Neil Gehrels Swift Observatory.

<sup>7</sup> <http://www.svom.fr>

The essential point here is simple: the value of a discovery is relative. In the nascent phase of a subject, initial secure detection(s) are trail blazing. As the subject progresses, mere detections while also termed as discoveries constitute increasingly poor return of understanding. In order to make advances, additional data (e.g., afterglow) are needed to make the detected candidates to have some value. In that sense the process of “discovery” becomes longer (and usually distributed over several efforts).

I conclude this section with two points. First, there is a striking parallel between the historical development of the GRB field and that of Fast Radio Bursts (FRBs), except the development of FRB field is proceeding a much faster rate, relative to that of GRBs (Kulkarni 2018). Second, I note that over the course of the mission lifetime, *Swift* now essentially acts like “GRB Utility”<sup>8</sup> – a reliable source of usable products (time of explosion, arcsecond position and early afterglow light curves). In a fundamental way, this transformation is a direct indicator of the maturity of the field. After having studied over several thousand GRBs, even an astronomer who is devoted to GRBs would not be willing to chase every GRB. Instead, astronomers review the Swift data products and define sub-samples that are worthy of further study. I predict that in less than five years the field of FRBs will have their own “FRB Utilities”.

The continuing success of the aging *Swift* mission motivates me to suggest here an “Optical Transient Utility” – a reliable supplier of nightly cadenced light curves along with spectral classification for all transients satisfying a brightness flux limit or a distance limit. Astronomers with patience will use the large data base to quantitatively model the transient phenomena (rates, subtypes, yields and so on) whereas interested in action will be on the lookout for unusual events or selected samples to undertake deeper (follow up) studies. This Utility idea is fully developed in §6.

### 3.2. The Discovery Process for Supernovae

For extragalactic optical transients, unlike GRBs, it is not possible to make firm identifications of the nature of the transient based on a few initial multi-band photometric points. Considerable additional information, either in the form of a classification spectrum or an extensive multi-band light curve is needed to securely classify the transient. In some sense, this is the equivalent of the information supplied by the afterglow phenomenon. Finally, to set the energy scale of the event, we need to know the redshift (or distance) to the event.

Next, the transient optical sky is more fecund than the transient gamma-ray sky. For instance, the annual all-sky rate for supernovae is about 32000 for peak magnitude of 20 (Feindt et al. 2019). Going even a magnitude fainter will dramatically increase this rate. These rates are so large that it is a capital mistake to measure the anticipated impact of a new facility by the expected yearly haul of transient candidates.

In my view, going forward, a *useful* discovery of a SN involves four distinct steps which are discussed below.

#### 3.2.1. Detection of an event

The first step is detection of an event. At the present time, this step is provided by imaging surveys.<sup>9</sup> The latest image is compared to a reference image and sophisticated algorithms employed to reject imaging and instrumental artifacts and poor subtractions. The next step is to determine whether the event is a transient.

#### 3.2.2. Purity of the Candidate

Before addressing the technical details I want to clearly address an important but sticky issue: “what is a transient?”. All astronomers would agree that asteroids or variable stars are not transients. All astronomers would also agree that the term transient should be applied to singular (“one-off”) events which are accompanied by a dramatic rise in the flux. From decades of study we know that such events involve wholesale destruction of an object or a massive rearrangement of the system. By this criteria, at the present time the set of transients include supernovae of all sorts, stellar mergers of all sorts and tidal disruption events (TDEs).

However, there is likely to be some dispute about eruptive variables: classical novae and related variables (e.g., dwarf novae), type I bursts, soft x-ray transients, x-ray novae, supernova imposters and flare stars (and related phenomenon) variables. In these objects the events arise from surface explosions, rapid changes in accretion rate or magnetic reconnection. I advocate that we call such violent but recurrent events as eruptive variables.

The second step is to determine the confidence in the detection of the transient – the purity. The false positives are moving objects, variable stars and eruptive stars. To this end, the observing team would likely have employed one or more strategies to cull out moving objects (e.g., by undertaking two observations, separated

<sup>8</sup> As in a water or electric utility.

<sup>9</sup> Though, as time goes by, DESI and other massively multiplexed spectroscopic surveys, will give rise to a cottage industry of “spectral transient candidates”.



by an hour).<sup>10</sup> Quiescent counterparts are expected for variable stars including eruptive variables. Deep multi-band images (e.g., PS-1, WISE, GALEX) can be used to search for the counterparts and thus filter out the eruptive variables. Finally, contextual information (e.g., a diffuse object next to a transient is likely to be the host galaxy) can be used to enrich the transient yield.

The interested reader is directed to Appendix A where I provide summaries of the classification strategies employed by the major groups involved in ongoing optical TDA surveys.

### 3.2.3. *Announcing the candidate*

Some groups are internally organized to both detect, classify and follow up the sources. Examples include dedicated type Ia supernovae and private surveys carried out with ZTF. For groups or surveys without such built-in capability, prompt communication of the transient opens up the possibility of follow up (multi-band, multi-“messenger”) astronomy. At the present time, this step is accomplished by astronomers uploading the vital statistics of the transient to TNS.

In this context I bring up the possibility that there could be two different epochs: the epoch of the “first detection” and the epoch at which the event is reported to the TNS. Some groups may be adventurous and report the first detection whereas others may wish to see a second detection before uploading a candidate to TNS. Given this situation, it would be helpful for the community to have both these events included in the AT data base. However, the time honored and the most fair way to settle issues of “claim” is to link the AT to the group which reported first. I will admit that this rule is likely to tempt some astronomers to register events with modest significance. A solution is for a “ratings” group to keep a track of the quality of the events reported by various groups or brokers (and addressed in §7.3).

### 3.2.4. *Linking the transient to known classes*

The last step is to decisively link the transient to a major class of explosions. In almost all cases, a quality spectrum leads to definitive classification. SN spectra are sufficiently unique to distinguish them from flaring stars and Galactic eruptive variables. Separately, spectra provide a decent estimate of the redshift which sets the physical scale of the event. Other alternatives include multi-band light curves, which are discussed in §5.

<sup>10</sup> At the bright end, say 18 mag, the asteroid catalog is quite complete and so one could review the candidate against the ephemerides of asteroids.

**Table 1.** AT candidates sorted by survey telescopes

Imaging Telescope	<i>n</i>
ZTF	6922
PS-1	5324
Gaia	2929
ATLAS	2211
ASAS-SN	256
DECam	190
MASTER	122
OGLE	109

NOTE—*n* (column 2) is the number of ATs first reported by telescope (column 1). The histogram has been cutoff at number of ATs,  $n < 100$ .

Taken together, the four steps described above constitute the “discovery” of an extragalactic optical transient. Given this multi-stage effort, it is important to credit “discovery” in a fair and equitable way. It will be increasingly the case that the detection of the transients will be undertaken and disseminated by one or more surveys, the alerts will be processed for purity by one more “brokers” (or their subscribers) and finally one more observers will undertake key follow up observations.

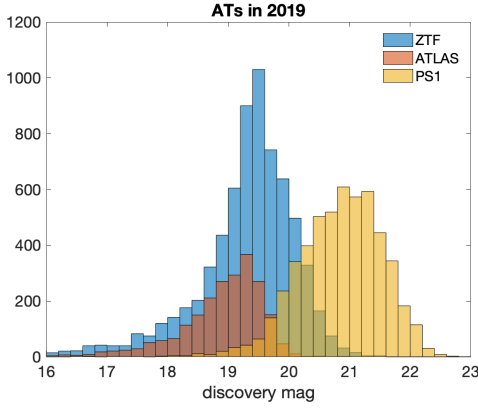
## 4. ASTRONOMICAL TRANSIENTS & SUPERNOVAE IN 2019

From the TNS website, using a program I had written (Kulkarni 2020), I downloaded, on 22 March 2020, the AT master catalog for the year 2019. I found a total of 18296 entries of which 1012 were classified as SNe. Each AT is summarized by a record which consists of 24 fields. At this point in time, all candidate events are found via imaging (photometric) surveys. Some surveys operate without filters whereas others use traditional filters. It is reasonable to approximate all reported magnitudes as “V” band.

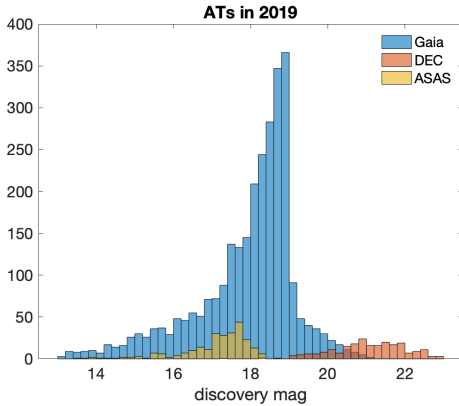
The first four fields are basic: ID (record index), AT Name, RA and Dec. A number of key words are related to photometric detection: the name(s) of photometric surveys (“Discovery Data Source/s”, field 10), the internal name of the source (“Discovery Internal Name”, field 13), the name of the imager (“Discovery Instrument/s”, field 14), the magnitude upon the first detection (“Discovery Mag/Flux”, field 19), the “Discovery Filter” (field 20) and the date of the first detection

(“Discovery Date”, field 21). The “Reporting Group/s” can be found in field 9.

The fields related to spectroscopic observations are as follows: field 6 (“Redshift” of the transient), field 8 (“Host Redshift”), field 11 (“Classifying Group/s”) and field 15 (“Classifying Instrument/s”). In almost all cases a spectrum leads to a secure classification of the event and is recorded in field 5 (“Object type”).



**Figure 1.** Histogram of the magnitudes upon detection of ATs reported in 2019 for ZTF, ATLAS and PS1. ATLAS and PS1 self report (§A.1). Several groups receive ZTF alerts and submit their own reports: Bright Transient Survey (§A.4), AMPEL (§A.3) and ALerCE (§A.2).



**Figure 2.** The same as in Figure 1 (but with a reduced y-axis scale) for *Gaia* (§A.5), DECam (in the course of pursuing GW events) and ASAS-SN.

An inspection of the 2019 data shows the following distribution for Object Type: null value (15987 events), SN (1932 events), TDE (5 events), ILRT (Intermediate Luminosity Red Transients; 1 event) and a total of 101 events covering the set [AGN, CV, Galaxy, LBV, Light-Echo, M dwarf, Nova, QSO, Varstar]. Only for events with Object Type=SN will the forename change from

AT to SN. No equivalent rechristening takes place for any other transients such as TDE or ILRT.<sup>11</sup>

Using the first name<sup>12</sup> in field 10 I link each AT to its discovery survey. The resulting histogram of candidates with respect to the originating surveys can be found in Table 1. As can be seen from this Table, the dominant contributors are ZTF, PS1, *Gaia* and ATLAS. The histogram of the magnitude of the first detection is shown in Figure 1 and Figure 2. From this Figure, it is clear that PS1 is the most sensitive survey followed by ZTF, ATLAS and *Gaia*.

One of the unexpected surprises is that supernovae can inform us of how complete are our catalogs of galaxies. The luminosities of galaxies can vary over eight orders of magnitude whereas supernovae, especially type Ia, are famous for their constancy (and brilliance). Thus, supernovae are excellent beacons of galaxies and with a modest effort, type Ia supernovae can be used to make precise assessment of the completeness of catalogs of nearby galaxies (Kulkarni et al. 2018). In view of this connection, it is interesting to report plausible host galaxies of supernovae. In fact, this information can be found in field 7 (“Host Name”). Analysis of the host names is presented in §B.1.

#### 4.1. Statistics of Classified Events (Supernovae)

An inspection of the TNS master catalog for 2019 shows that only 1012 of the ATs were classified as SNe. The histogram of the discovery magnitudes of the SNe is shown in Figure 3.

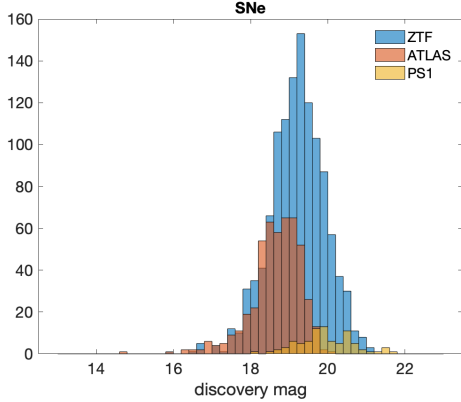
In Table 2 I provide a histogram of the telescopes/instruments which undertook these classifications. The distribution in this table is not necessarily reflective of the sensitivity of the spectrographs but also of the priority accorded to spectral classification. For instance, the EFOC2+NTT has considerable capacity to classify but the key project ePESSTO<sup>13</sup>, which has been granted 90 nights per year, has also in its ambit detailed spectral studies of a variety of transients.

The SEDM (Spectral Energy Distribution Machine or SEDM) was designed to solely classify supernovae. Extragalactic transients have significant expansion velocities ( $v/c \gtrsim 0.01$ ) and so a spectral resolution,  $R = \lambda/\Delta\lambda$  of 100 is sufficient for classification. Thus the SEDM with  $R \approx 100$  trades spectral resolution for telescope aperture (see §C for details). It is for this reason that the SEDM mounted on a mere (but dedicated) 60-inch

<sup>11</sup> “As of this point” – Ofer Yaron, Curator for TNS.

<sup>12</sup> The field can contain several “discovery data” sources, separated by commas.

<sup>13</sup> <http://www.pessto.org>



**Figure 3.** As in Figure 1 a histogram of the magnitudes upon discovery but of classified SNe.

**Table 2.** Classifying Instruments & Telescopes

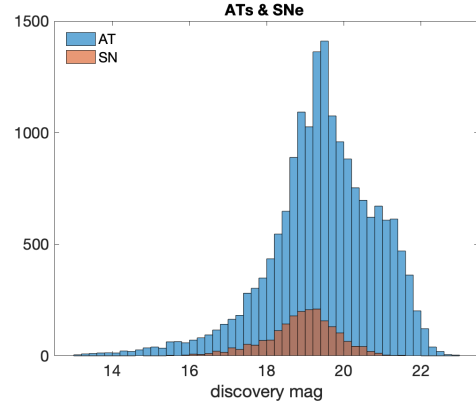
Telescope-Spectrograph	$n_s$	%
P60 - SEDM	810	40.3
ESO-NTT - EFOSC2-NTT	294	14.6
LT - SPRAT	215	10.7
P200 - DBSP	154	7.7
anon	95	4.7
UH88 - SNIFS	94	4.7
Lick-3m - KAST	63	3.1
APO-3.5m - DIS	42	2.1
Ekar - AFOSC	41	2.0
FTN - FLOYDS-N	32	1.6
SOAR - Goodman	30	1.5
LCO-duPont - WFCDD	23	1.1
Lijiang-2.4m - YFOSC	22	1.1
FTS - FLOYDS-S	18	0.9
Magellan-Baade - IMACS	16	0.8
Magellan-Clay - LDSS-3	10	0.5

NOTE— $n_s$  (column 2) is the number of spectra observed with the telescope-spectrograph (column 1) whereas column 3 is the ratio of  $n_s$  to the total number of classification and expressed as a percentage. Here, “anon” refers to those spectra for which there is no telescope-spectrograph entry. The histogram has been cutoff at  $n_s < 10$ .

telescope is able to account for 40% of the global SN spectral classification (see [Fremming et al. 2019](#) for the target throughput of SEDM).

#### 4.2. The Bottleneck

My analysis shows 1800 events have only one classification spectrum, 202 have two spectra and nine have three spectra. SN 2019clp is distinctive for having six spectra. Figure 4 graphically summarizes the “bottleneck” problem. The bottleneck factor, defined as the ratio of the identification of transients to spectral classification is nearly 10.



**Figure 4.** As in Figure 1 a histogram of the magnitudes upon discovery of all ATs and SNe reported in 2019.

An astute reader is likely to be surprised by the divergence between ATs and SNe at the bright end. I present an analysis of the origin of this divergence in §B.2.

#### 5. SPECTRAL CLASSIFICATION & REDSHIFT: FOUNDATIONAL VALUES

Going forward, we assume that improvements in image differencing algorithms and increasingly sophisticated filtering algorithms would have gotten rid of events arising from instrumental artifacts and that archival and contextual data will be used, along with sophisticated Machine Learning algorithms, to better classify events: asteroids, Galactic variables, flare stars, eruptive variables, burbling AGN and extragalactic explosive events.

From Table 3 we see that SNe dominate the demographics of extragalactic explosions. So the path to all other transients, especially the rare transients, requires a masterful understanding of SNe, if only to eliminate them in the quest for, say, kilonovae.

[Minkowski \(1941\)](#) introduced classification based on spectroscopy. The initial classification was type I (Hydrogen absent) and type II (Hydrogen present). Over time, spectral sub-types (Ib, Ic, IIn) and light curve based subtypes (IIL, IIP) were introduced (see [Filippenko 1997](#)). For completeness, at the suggestion of my colleague, Anders Nyholm, I mention the pioneering work of Piotr Kulikovsky (1910–2003) who published

**Table 3.** Local Volumetric Annual Rates of Extra-galactic Explosions

Class	$\mathcal{R}$ ( $\text{Gpc}^{-3} \text{ yr}^{-1}$ )	Ref.
Thermonuclear SNe	$3 \times 10^4$	[1]
Core-collapse SNe	$7 \times 10^4$	[2]
SLSN	$\approx 100$	[3]
TDE	$\approx 700$	[4]
LLGRB	$\approx 200$	[5]
LGRB <sup>†</sup>	$\approx 3$	[5]
SHB <sup>†</sup>	$\approx 2$	[5,6]
BNS	$< 800$	[7]

NOTE—The annual volumetric rates at  $z \approx 0$ .

Thermonuclear supernovae cover the entire class of type Ia supernovae and are expected to be powered by fusion. Core-collapse events can have hydrogen but their power source is ultimately gravitational collapse. Some of them could be powered by subsequent engine activity. The acronyms are as follows: super-luminous supernovae (SLSN), tidal disruption events (TDE), low luminosity gamma-ray bursts (LLGRB), long duration gamma-ray bursts (LGRB), short hard bursts (SHB) and binary neutron star coalescence (BNS).

<sup>†</sup>No correction for beaming. The multiplier could be as high as 100.

References: [1] Li et al. (2011). [2] Ho et al. (2020). The total rate is from Li et al. (2011) but this reference gives a break down between II, Ibc, Ic-BL etc. [3] Quimby et al. (2013). [4] S. van Velzen (pers. comm.). [5] Sun et al. (2015) [6] Dichiara et al. (2020). [7] Kasliwal et al. (2017).

a classification system also based on light curves (Kulkovskiy 1944; see Litvinova & Nadezhin 1983 for a modern citation). This system distinguished between four types of supernovae and found that some classes of supernovae favored star-forming galaxies and others late-type galaxies.

I offer the following *ansatz*: about one hundred data points are needed to make a fairly secure classification. These points could either be a low resolution optical spectrum or a multi-band light curve with tens of epochs properly sampled.<sup>14</sup> However, in either case we need to

know the redshift of the transient. A spectrum of the transient will not only provide a robust classification<sup>15</sup> but also readily result in the redshift of the transient (or the host). For high redshift transients, say  $z \gtrsim 0.3$ , multi-band photometry of the host galaxy will be adequate to get a useful estimate of the redshift (Collister & Lahav 2004) and thus set the energy scale.

The above discussion suggests a bifurcation in the methodology of the study of transients: the photometric time series method which is well suited to the numerous but faint transients,<sup>16</sup> and spectral classification for bright transients, which will be necessarily fewer relative to the population of faint transients. The faint transients will be largely at high redshifts (for which the photometric method will provide a usable redshift) while the bright transients, in each category, will be at low redshifts.

## 6. A PUBLIC TRANSIENT UTILITY

Earlier we noted that there has been a profound shift in transient object astronomy, namely, astronomers are already seemingly overwhelmed by the transient candidate discovery rate. Next, we found that spectral classification observations for only a tenth of the transient candidates are being undertaken. I review the near-term landscape whilst keeping these two conclusions in mind.

The next major development in the TDA field is LSST.<sup>17</sup> The great strengths of LSST are (1) photometric accuracy and precision, (2) superior astrometric precision for faint objects and (3) accurate knowledge of the point spread function. As a flagship survey, LSST has to respond to many constituencies. The resulting slow cadence of LSST is well suited for the study of slowly varying transients (such as SLSN) including cosmological Ia supernovae, lensed supernovae, thanks to the time dilation factor of  $1 + z$ . There are plans to set aside a small amount of time for moderate to high cadence studies of selected fields. Given the high density of faint events, such “mini” surveys are well suited to explore the phase space of faint and fast events. In particular, with these mini-surveys, LSST, because of its depth, is well positioned to undertake a comprehensive investigation of relativistic stellar explosions and related phenomenon (especially orphan afterglows).

<sup>15</sup> For obdurate sources, a repeat spectrum usually clarifies.

<sup>16</sup> In fact, the Transients and Variable Stars science working group of LSST has initiated a major program to precisely address this issue: Photometric LSST Astronomical Time-Series Classification Challenge (PLAsTICC); see <https://plasticc.org>.

<sup>17</sup> Given the delays due to COVID-19, a plausible schedule for full operations, including routine real-time release of alerts, of the Rubin Observatory is early 2024.

<sup>14</sup> For instance, for a flare star, you would need sampling on timescales of minutes to hours and for SLSN, sampling on timescales of weeks to months is adequate.



In reverse, the areal density of objects decreases with increasing brightness. Thus, for the brightest phenomenon one needs an all-sky survey. At the present time, this is the value that ASAS-SN provides, given the on-going wide-field surveys (ATLAS, PS-1, ZTF). In the same way, in the LSST era, we need to have wide-field nightly cadenced sky survey(s) to operate in conjunction with LSST. Accepting this conclusion and motivated by the success of *Swift* “GRB Utility” (§3.1) I propose an integrated “Optical Transient Utility”. This facility will, night after night, produce densely sampled light curves along with the “ground-truth” provided by spectral classification. The resulting data will be complementary to LSST and, equally importantly, produce the foundational data for Machine Learning algorithms which can then be applied to large samples of faint transients with modest number of photometric points. Separately, other astronomers could undertake detailed studies of interesting objects (based on light curves or spectral classification or association with other surveys such as the Spekr RG<sup>18</sup>).

As with *Swift* all data will be released in near-real time. For rapidly evolving transients (e.g., young supernovae) it is critical that the alerts carry a light curve history with force photometry (including rigorously specifying upper limits). Spectral classification observations will be undertaken for a well-defined sample of candidates and data released in real time. A monthly release of archive quality images and light curves would be helpful for stellar astronomy.

A facility as described above, especially with the listed demands, will come with a cost. However, the cost can be justified by noting that the utility will serve the entire astronomical community. Below, I discuss two specific key projects which form the backbone of the proposed Transient Utility: a flux-limited sample and a volume-limited sample.

**Bright Transient Survey (BTS).** Flux-limited surveys have been a corner stone of astronomy. A recent example of such a survey is the ZTF BTS (Fremling et al. 2019). The estimated annual all-sky supernova rate (Ia and core-collapse) is [2200, 4300, 8400, 16231, 31478] for peak magnitude of [18, 18.5, 19, 19.5, 20] (Feindt et al. 2019). A large sample would allow for detailed studies relating supernova types to host galaxy parameters. A large sample would result in a bigger “ground truth” data base for ML algorithms. Finally, the large size of the sample permits intense searches for rare types. A

sample focused on nearby transients allows for the discovery of watershed events such as AT2019cow (Prentice et al. 2018).

Supernovae of type Ia have played an outsized role in the development of modern astronomy. The determination of large scale mass distribution is a major goal of modern astronomy. In a purely Hubble flow, the velocity of the host galaxies would be the same as that computed from the Hubble law applied to the distance given by Ia SNe. However, large fluctuations in matter (dark and otherwise) result in the two velocities being discrepant with the difference velocities (peculiar velocities) acting as tracers of matter. As noted by many authors this opens up the possibility of constructing the local matter makeup (e.g., Sasaki 1987; Gordon et al. 2007; Huterer et al. 2017). In fact, in this regard, there are several on-going efforts but based on using the Fundamental Plane relation for elliptical galaxies (6dFGS, TAIPAN) or Tully-Fisher relation for spiral galaxies (e.g., WALLABY on ASKAP).

The strength of SN Ia sample is the precision of the distance estimate and the weakness (relative to the galaxy methods) is the smaller sample size. Several recent studies have investigated this method in considerable detail and find that the SN approach is promising provided the SN sample is in the many thousands (see, in particular, Agrawal et al. 2019; Graziani et al. 2020; Kim & Linder 2020). In addition to determining the mass make up on local scales (comparable to the Baryon Acoustic Oscillation, BAO, scale), the same observations can determine the growth index,  $\gamma$  where  $f \propto \Omega_M^\gamma$  with  $f$  is the linear growth rate and  $\Omega_M$  is the ratio of the matter density to critical density.

The main issue is the size of the sample. A sample size of 6000 type Ia supernovae will more than match the planned galaxy surveys (Jakob Nordin, pers. comm.). ZTF alone is already classifying nearly a thousand Ia supernovae per year. If we stick to 19.5 mag and only consider supernovae which go off in the night sky the yearly haul of the proposed Transient Utility will be about 5000 per year. With such large yields, as discussed by (Agrawal et al. 2019), by combining the proposed BTS with higher redshift studies, the mass of the sum of the masses of neutrinos and uncertainties in the cosmographic parameters  $a$  and  $w$  can be constrained.

Incidentally, a standard type Ia at a distance of 400 Mpc will peak at 19 mag. Such “bright” supernovae can help astronomers assess the completeness of catalogs of nearby galaxies (Kulkarni et al. 2018; Fremling et al. 2019).

<sup>18</sup> <http://www.iki.rssi.ru/eng/srg.htm>

**Transients in the Local Universe.** BTS will favor bright supernovae such as type Ia supernovae, super-luminous supernovae (SLSN) and Tidal Disruption Events (TDEs). A natural counterbalance to BTS is a volume limited survey, perhaps titled as “Transients in the Local Universe” (TILU). Such a survey will be sensitive to core-collapse supernovae and other intrinsically sub-luminous supernovae. Equally importantly it is the detailed study of the nearest events (which are necessarily brighter) which usually provide the best laboratory for understanding the origins. Such volume limited surveys on a large scale are now being carried out by ATLAS and ZTF.

The success of TILU will depend directly on the completeness of catalogs of nearby galaxies (Kulkarni et al. 2018). Fortunately, the era of massively multiplexed spectrographs has begun. In particular, Dark Energy Spectroscopic Instrument (DESI)<sup>19</sup> will, amongst other surveys, undertake an ambitious spectroscopic survey of bright galaxies in the Northern sky.

The limiting radius should be large enough to encompass most types of extragalactic explosions. To this end, I present local rates of various transients in Table 3. The volume need not include rare events which are distinctive. Examples include classical GRBs (distinctive by their high energy spectral and temporal features) and super-luminous supernovae (distinctive by their long duration light curves). A radius of 200 Mpc nicely includes the horizon set by high energy cosmic rays and by the detection sensitivity of gravitational wave interferometer for binary neutron star coalescences (Kulkarni et al. 2018). Again, restricting to transients which go off in the night sky we expect 1700 transients/year within 200 Mpc (see Table 3).

LSST will play a great role in the TILU survey. The sensitivity of LSST means that an explosion in a cataloged nearby galaxy will be detected at early times. The primary contamination will be novae but any transient that is brighter than, say,  $-10$  mag can be safely assumed to be not a nova. In such cases astronomers can start undertaking spectroscopic observations with the shallow surveys providing the full light curves. Next, it appears that some (many) core-collapse supernovae, across all sub-types, exhibit bumps and burps before they explode (Smith 2014 provides a good starting point for the physics of mass loss in massive stars; see, for example, Fuller & Ro 2018 for models). Given this development it is easy to predict that for all bright su-

pernovae, LSST will provide a unique insight into this phenomenon.

### 6.1. Implementation

The proposed utility has two elements: an imaging element and a spectral classification element.

#### 6.1.1. Imaging Facilities

The imaging element requires imaging the entire night sky, at least once a night, ideally in several bands, to a limiting magnitude of 20 mag. This magnitude limit is set by the capability of the spectroscopic element (described next).

Fortunately, the essential elements for the proposed survey already exist in the form ATLAS, PS-1 and ZTF. Additionally, BlackGEM, a wide-field optical TDA survey based at La Silla (Bloemen et al. 2015), is expected to start operating soon. Finally, ATLAS is on course to adding stations in the Southern hemisphere (J. Tonry, pers. comm.). The (single exposure) sensitivity for these surveys range from 19.5 to 21.5 mag. Thus, it is a matter for funding agencies or foundations to entice the operators of these facilities to participate in a coordinated public survey.

#### 6.1.2. Spectroscopic Facilities

For the spectroscopic element there are two components: classification of bright transients (19 mag, peak) and fainter transients (say 20 mag). For the former, classification observations can be scheduled to take place close to the peak whereas for the latter, it would be ideal to observe upon first detection.

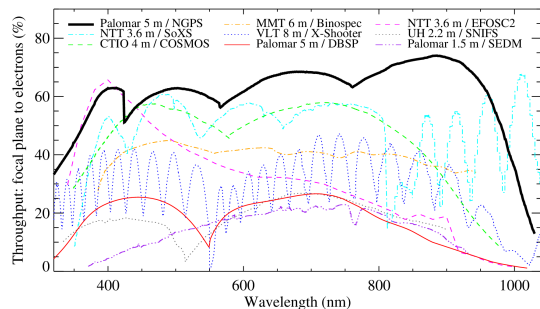
From Table 2 we see that the SEDM has proved itself to be workhorse for 19 mag events, even though it is mounted on a 60-inch telescope. The SEDM with its unusual choice of ultra-low resolution dispersion and robotic acquisition was built specifically for classifying extragalactic transients. The spectral classification for BTS can be undertaken with, say, three 2-m class telescopes (one in the North, one in the South and one close to the equator and ideally separated in longitude) equipped with spectrometers tuned for classification. Motivated thus, we are considering the possibility of an SEDM on the robotic Kitt Peak 84-inch telescope (Coughlin et al. 2019).

The events in the TILU survey will be, in the mean, fainter than those of the BTS. Fortunately, successive generations of spectrographs have seen an increasing throughput. For instance, consider the Next Generation Palomar Spectrograph (NGPS), a low resolution spectrograph that is currently being built for the Palomar 200-inch telescope. It has a slit-to-detector throughput of 80% (Figure 5). Two 4-m class telescopes, one in the

<sup>19</sup> <https://www.desi.lbl.gov/>

North and the other in the South, equipped with modern low resolution spectrographs, would be sufficient for this purpose.

In addition to re-prioritizing existing telescope+spectrographs there is the possibility of new spectroscopic facilities based on arrays of small telescopes (Eikenberry et al. 2019). In this spirit of novel approaches, I suggest, based on the experience accrued from the SEDM that there is a compelling opportunity for considering low resolution spectrographs optimized solely for SN classification. Perhaps a funding agency or a foundation could call for a global competition for innovative solutions to this important and pressing need. Following the down selection, replicas of the system can be built and deployed at telescopes, host institutions willing, around the world.



**Figure 5.** The throughput from the focal plane to photoelectrons of the Next Generation Palomar Spectrograph (NGPS; solid line). The throughput for other spectrographs varies between this measure to “from sky to photoelectrons”. References: Son of X-Shooter (SoXS, Claudi et al. 2018, M. Genoni, pers. comm.), COSMOS (Martini et al. 2014), Binospec (Fabricant et al. 2019), X-Shooter (Vernet et al. 2011), DBSP (Oke & Gunn 1982), EFOSC2, which is part of PESTO (Smartt et al. 2015), SNIFS (Lantz et al. 2004; Lombardo et al. 2017), and SEDM (Blagorodnova et al. 2018). Figure supplied by E. Kirby.

## 7. CONCLUSIONS

In this report I have focused on the future of extragalactic transients, especially those which are bright enough ( $\lesssim 20$  mag) to allow for routine follow up studies with existing telescopes. For fainter transients, much of the study will involve analysis of multi-band photometric time series from which a highly selective group will be followed up spectroscopically.

I propose a public “Optical Transient Utility”, based on existing (and soon to be commissioned) moderate aperture wide-field surveys. Specifically, a survey(s) which cover the entire night sky and with sensitivity to readily detected transients with peak magnitude  $\lesssim 19.5$  (which, in practice means, a secure detection at

$\gtrsim 20.5$  mag). The magnitude limit was chosen so that spectroscopic classification of most transients can be carried out. Thus a necessary part of the Utility are two or three 2-m class telescopes equipped with spectrometers tuned for spectral classification of supernovae as well as a pair of 4-m class telescopes equipped with low resolution spectrometers for detailed spectroscopic studies or early studies of young supernovae (which will be fainter than 19.5 mag) or both.

The flux limited transient+spectral survey is of considerable value to (1) continued exploration of the phase space of extragalactic transients, (2) low redshift cosmology including inferring the structure of mass on local Baryon Acoustic Oscillation (BAO) scales, (3) rates of all sub-types of supernovae and tidal disruption events and (4) accurate measure of the completion fraction of catalogs of nearby galaxies (few hundred Mpc). In contrast, the volume limited transient+spectral survey allows for studies of the faint end of the luminosity function of supernovae and young supernovae.

The primary value of the large projects described above come from systematic analyses of their vast database. Fortunately, two archives have sprung up to meet this demand: the “Weizmann Interactive Supernova Data Repository” (Yaron & Gal-Yam 2012) and the “Open Supernova Catalog” (Guillochon et al. 2017).

### 7.1. Critical Role of Astrominformatics

The rise of TDA surveys was driven by exponential growth in hardware: format growth of detectors, inexpensive computers for data taking and analysis and perfection of the detectors. Going forward the major gains for TDA surveys lie in development and application of clever algorithms and software methodologies, aka, “astro-informatics”.

Optical TDA surveys are now sufficiently technically mature that events that they label as transients are genuine astrophysical events. In decreasing order they will be supernovae (of all sorts), eruptive variables (in particular, dwarf novae), flare stars and asteroids (at turning points). For the moment let us consider the case of an astronomer interested in supernovae. For this person, the probability of the candidate not being a supernova is the false positive probability (FPP). In contrast, the false negative probability is the probability that the candidate is a supernova but the algorithm has classified at not a supernova.

The tolerable level of FPP depends on the circumstances. Those who are undertaking a large survey would probably prefer  $FPP \lesssim 0.03$ . On the other hand, someone interested in studying young SNe may be willing to tolerate  $FPP \approx 0.1$  so that they will not miss a

“golden” event. The key point is that the published FPP will determine the follow up destiny of the candidate.

### 7.2. *Clearing Houses*

To first order we have three types of (apparently and otherwise) time variable sources: moving objects, variable stars in which I include eruptive variables, varying AGN and geometric illusions such as lensing events and transients. Fortunately we have two of three clearing houses: TNS (§2) and the Minor Planet Center<sup>20</sup> which is “responsible for the designation of minor planets, comets, and natural satellites in the solar system. The MPC is also responsible for the efficient collection, computation, checking, and dissemination of astrometric observations and orbits for minor planets and comets”.

TNS, the clearing house of ATs, is now central to TDA surveys. Going forward, TNS will play an even more crucial role. To start with, as extensively discussed in §3.2, the “discovery” process will be likely be spread over several groups. TNS, via appropriate keywords, will have to accommodate the emerging distributed discovery process. Next, following the discussion in the previous section TNS should require that groups uploading candidates to the TNS also provide FPP. In the same spirit, observers/brokers should be able to update the probabilities as more data are collected.

At the present time we have no IAU approved clearing house for variable stars. In the past, astronomers at the Institute of Astronomy, Russian Academy of Sciences, maintained the “General Catalogue of Variable Stars”<sup>21</sup> (see Kulkarni 2016 for a brief history of catalogs of variable stars). In my view (*ibid*), the field of stellar astronomy is undergoing a second renaissance. If this thesis is accepted then astronomers would be well served with a major clearing house for variable stars which, for the arguments presented throughout this paper, should also include eruptive stars.

### 7.3. *Ratings Agencies*

Given the anticipated reliance on measures such as FPP (§7.1) it is important that brokers for surveys report FPPs. This issue is urgent given the analysis presented in §B.2. As in commercial life, “ratings” agencies are needed to provide an independent assessment of the quality of candidates reported by surveys. It would be useful for the appropriate working group of the IAU

(Time Domain Astronomy, perhaps) to discuss this matter and motivate the community to develop such centers.

### 7.4. *An Exciting and Endless Frontier*

With little doubt LSST will bring in unanticipated discoveries from its powerful exploration of the faint events. LSST is very well suited to finding sub-luminous events, both near and far, that have been missed by on-going shallow surveys. Entirely separately, there are efforts to (1) explore the optical sky on timescales of seconds and (2) search large swaths of the sky with clusters of small telescopes for optical counterparts to GW sources.<sup>22</sup> Both these developments were made possible by the availability of inexpensive but high performance CMOS (Complementary Metal-Oxide Semiconductor) detectors. Tomo-e-Gozen is a massively-mosaicked CMOS camera with a field-of-view of 20 deg<sup>2</sup> and is mounted on the Kiso 1.05-m Schmidt telescope (Sako et al. 2018). See Ohsawa et al. (2019); Richmond et al. (2020) for a taste of the future. Separately, there are stirrings of TDA in the near IR band (NIR; see, for example, Kasliwal et al. 2019a). It is a pity that the US is not investing in wide-field UV TDA – one of the last and rich (laden with low hanging fruits) frontiers of TDA.

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<sup>20</sup> <https://www.cfa.harvard.edu/content/minor-planet-center-mpc>

<sup>21</sup> <http://www.sai.msu.su/gcvs/>

<sup>22</sup> See for example, <https://evryscope.astro.unc.edu/>  
<https://goto-observatory.org/> <http://ddoti.astroscu.unam.mx>  
<https://www.weizmann.ac.il/physics/ofek/research-activities/instrumentation-0>



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## APPENDIX

## A. CRITERIA FOR REGISTERING ASTRONOMICAL TRANSIENTS WITH THE TNS

A.1. *PS-1 & ATLAS*

Queen’s University of Belfast (QUB), under the leadership of S. Smartt, is in charge of registering transients arising from PS-1 and ATLAS. The alert schema is described in [Smith et al. \(2020\)](#). The stated goal is to “register candidate extragalactic explosive transients as AT.” To this end, the following types of events are rejected: (i) anything coincident with a Galactic stellar source; (ii) obvious Galactic CVs and novae; (iii) obvious Galactic M-dwarf flares; (iv) novae in nearby galaxies (M31, M33, M81 and others); (v) known AGN or clear variability in a galaxy core (as opposed to a high contrast flare, which could be a TDE). At low latitudes, faint stellar-like candidates are rejected.

ATLAS is pursuing a key project to follow up all candidates, regardless of the candidate detection survey, that are in the vicinity (up to 50 kpc) of known galaxies within 100 Mpc. This survey, has already yield the famous AT2018cow source ([Prentice et al. 2018](#)) and the faintest SN to date (2019gsc; [Srivastav et al. 2020](#)).

A.2. *Automatic Learning for the Rapid Classification of Events (ALeRCE)*

ALeRCE<sup>23</sup> uses a convolutional neural network (Carrasco-Davis et al. 2020, in prep.) to classify ZTF public alerts into five classes: asteroid, AGN, variable star, supernova and bogus. The focus of ALeRCE is to enable fast follow up of young SNe and as such classification is undertaken even if there is only one observation.

High-value candidates are automatically displayed at the “SNhunter” site<sup>24</sup>, only seconds after being ingested from the ZTF alert stream. After the end of night in California, three people (“checkers”) visually inspect the top one hundred SN candidates. The following events are registered to TNS: events which are near-extended sources (putative host galaxies) and which have a PSF-like shape (based on the ZTF stamps and reference PS-1 images at the location of the candidate); which are not near known solar system objects; and, finally, which have not been vetoed by any of the checkers.

NED, Simbad and SDSS are queried to review host galaxy properties (including redshift, if available). A lower limit for the magnitude rise rate is computed and reported if the rate exceeds 0.05 mag/day. Using these tools the group detected three SN candidates rising faster than one mag/day: ZTF19abueupg<sup>25</sup>, ZTF19abvdgqo<sup>26</sup>, ZTF20aaelulu<sup>27</sup> which were later classified as type II, Ib and Ic SNe, respectively. Between August 2018 and January 2020 the group has reported 1846 SN candidates with an average rate of 9.1 SNe/day. About two-third of them have shown a subsequent detection, while one third show just the first detection due to either being a very distant SNe near peak, an asteroid near an extended source, or a bogus candidates mistaken to be real. Over this period, a total 257 of the SN candidates reported to TNS have been spectroscopically classified by other groups.

A.3. *Alert Management, Photometry, and Evaluation of Light Curves (AMPEL)*

The AMPEL software platform has been developed to consistently apply analysis schema to heterogeneous data streams ([Nordin et al. 2019](#)). One of the applications has been to perform a selection of likely extragalactic transients from the ZTF alert stream and share these with the community through the TNS. The selection methodology was designed to simultaneously be reproducible, of high quality and have the capability to submit candidates in real-time to allow for fast follow-up. These goals were achieved through a fully automated selection process based on both alert properties and matches with static astronomical catalogs. As no human input is needed, the results carry no unknown selection biases and submission takes place within minutes of the initial ZTF observations. The selection quality, including false-positive and completeness rates, were examined through comparisons with data collected over the first months of ZTF operations (see [Nordin et al. 2019](#) for a full account).

Currently, two AMPEL TNS senders are active: ZTF\_AMPEL\_NEW only submits candidates with an age less than five days at the time of submission, thus catering to observers looking for quickly varying transients. ZTF\_AMPEL\_COMPLETE has no age criteria and is instead designed to create a complete, pure candidate stream but

<sup>23</sup> <http://alerce.science/>

<sup>24</sup> <https://snhunter.alerce.online>

<sup>25</sup> <http://dev.alerce.online/object/ZTF19abueupg>

<sup>26</sup> <http://dev.alerce.online/object/ZTF19abvdgqo>

<sup>27</sup> <http://dev.alerce.online/object/ZTF20aaelulu>

where the average age at submission will naturally be higher. Both senders operate in parallel and in addition to other TNS senders, thus allowing users to base follow-up decisions also on which senders submitted a transient. The two ZTF-AMPEL senders have to date submitted  $\sim 8000$  astronomical transients to the TNS, out of which  $\sim 1900$  were later classified as SNe. “The vast majority of the unclassified transients appear to be real but fainter transients.”

#### A.4. Bright Transient Survey (ZTF)

The Bright Transient Survey (BTS) is the largest SN survey undertaken by ZTF. This survey is described in [Fremling et al. \(2019\)](#). After the first year of the survey, the original simple rubric was replaced with a more complex series of cuts to decrease the reliance on human scanning and judgment (which by mid-2019 after reference imaging was completed, was requiring scanners to pick out 5 SNe out of 400+ candidates per night). The current filter, like the previous one, requires that sources be above the reference level and above 19.0 mag, that they be detected in two or more epochs separated in time by at least 30 minutes, and that they be outside the Galactic plane ( $|b| > 7^\circ$ ). Additionally, (1) sources with a minor planet match are explicitly rejected. (2) Sources are rejected if they have a ML real-bogus score less than 0.2. This threshold is increased to 0.35 within  $< 1''$  of  $< 17.0$  mag *Gaia*-catalogued objects and to 0.45 within  $< 1.5''$  of  $< 15.5$  mag *Gaia* objects. (3) Sources must also not have a “deep” ML score less than 0.1. (4) Sources are required to not be coincident within  $< 2''$  of a high-probability star (ML “stellarity” score  $> 0.76$ ), or within  $< 0.5''$  of a bright ( $< 17$  mag) object for which star/galaxy classification failed, or within  $< 1''$  of an extremely red stellar object ( $r - z > 3$  mag with stellarity  $> 0.2$ , a probable M-dwarf). They must also not be within  $1.5''$  of a  $< 15$  mag *Gaia* object or within  $1.0''$  of a  $< 16.5$  mag *Gaia* object, but only if the source is not new ( $< 15$  days and  $< 30$  days, respectively). (5) Sources even moderately close to very bright stars are rejected due to the frequency of artifacts in these regions. The event cannot be within  $20''$  of a  $r < 12$  mag probable star (stellarity  $> 0.49$ ) or a  $r < 14.5$  mag definite star (stellarity  $> 0.8$ ), within  $5''$  of a  $r < 15$  mag probable star, or within  $1.1''$  of a  $r < 16.5$  mag probable star. (Similar cuts are also applied with reference to *i*-band and *z*-band mags.)

Sources with a long history (time from first detection) are scrutinized more carefully, since the vast majority of such sources are AGNs or variable stars. If within  $3''$  of a  $< 16$  mag catalogued source and older than  $> 90$  days, the source is rejected. “Old” sources ( $> 90$  days) are also rejected if  $< 0.4''$  from a  $< 19.5$  mag catalogued source,  $< 0.8''$  from a  $< 17.5$  mag catalogued source, or  $< 1.2''$  from a  $< 15.5$  mag catalogued source. However, this rejection does not apply if the source is at a maximum in its light curve or if it has not been recorded at  $< 18.5$  mag more than twice in the past 30 days, to avoid missing SNe near AGNs or galaxy nuclei. Sources very closely coincident with *Gaia*-catalogued objects are also removed if “old” (specifically:  $< 0.35''$  from a  $< 17$  mag object if  $> 30$  days,  $< 0.20''$  from a  $< 18$  mag object if  $> 90$  days, and  $< 0.35''$  from a  $< 19$  mag object if  $> 300$  days and detected fainter than 18.5 mag).

Approximately 50 new sources pass these criteria during a clear night, of which about 5 are typically SNe and the rest are a mix of CV’s, AGNs variable stars, and a handful of artifacts which still pass through the above cuts for various reasons. (These numbers do not include sources that have already been saved during previous nights). Human scanners, aided by the GROWTH Marshal ([Kasliwal et al. 2019b](#)), using contextual information (typically whether the source is located within a galaxy and not coincident with a central point source, and whether its light curve is varying smoothly or erratically), reject the interlopers. Only a few minutes are required to scan and identify these sources on a particular night.

#### A.5. *Gaia*

*Gaia Science Alerts* system<sup>28</sup> ([Wyrzykowski et al. 2012](#); [Hodgkin et al. 2013](#)) is a part of the European Space Agency’s *Gaia* space mission ([Gaia Collaboration et al. 2016](#)) and is operated by the Institute of Astronomy of the University of Cambridge, UK, with the support of researchers from the University of Warsaw, Poland, SRON, NL and Konkoly, Hungary. *Gaia*, which has been operational since 2014, covers about  $1000 \text{ deg}^2$  over 24 hours and its data is transmitted to the ground on average every day. The typical delay between an observation and an alert is about 24–48 hours and typical cadence is 106 mins (due to the two mirror geometry of the instrument) and 30 days (due to scanning pattern). Alerts are defined as significant changes as measured by *Gaia* photometers (G-band; broad band optical). In the first two years of operation, *Gaia* Alerts delivered on average 1 alert per day, while now the rate is more than 10 transients/day. The detection pipeline is unbiased and is sensitive to both new sources (e.g., supernovae, cataclysmic variables) and old sources (e.g., micro-lensing events, AGN flares).

<sup>28</sup> <http://gsaweb.ast.cam.ac.uk/alerts>

The pipeline developed over years of the operation is capable of removing artifacts due to e.g., diffraction spikes from bright stars, or overlapping windows for stars in crowded regions. Note that *Gaia* mission processes its images on-board and what is delivered to the ground are positions and fluxes of detected objects brighter than about 20.5 mag. *Gaia* Alerts positional accuracy is about 0.1'' but that improves to tens of micro-arcseconds for reprocessed data published in subsequent data releases (Gaia Collaboration et al. 2018). A unique capability of *Gaia* is its low-dispersion ( $R \sim 70\text{--}100$ ) spectrophotometric measurements obtained for every individual observation with its Blue and Red Photometers (BP-RP), opening new possibilities for detection and classification of transients based on spectra, not just fluxes (Blagorodnova et al. 2014).

#### A.6. Optical Gravitational Lensing Experiment (OGLE)

OGLE has been operational since 1992. However, only since 2012 it started to deliver regular transient detections (Wyrzykowski et al. 2014). OGLE monitors about  $700 \text{ deg}^2$  of the sky, located around and between Magellanic Clouds, with a cadence varying from days to weeks. The OGLE Transient Detection System<sup>29</sup> uses difference imaging method and can observe transients as faint as 21.5 mag in I-band. Its long-term imaging history allows for detection of slowly evolving extragalactic transients.

I thank the following for contributing text to the sections above: S. Smartt (§A.1), F. Burón (§A.2), J. Nordin (§A.3), D. Perley (§A.4) and L. Wyrzykowski (§A.5 & §A.6).

### B. ADDITIONAL ANALYSES

#### B.1. Host Galaxies

Some reporting astronomers provide host galaxy information (“Host Name”, field 7). For the 2019 dataset, it appears that 1819 events, composed of 409 SNe and 1410 ATs, have this field populated. The histogram of the host galaxy catalogs is given in Table 4.

#### B.2. Bright Transient Candidates

In this section I investigate why some of the bright transients were not classified. As can be seen from Figure 6, some of this divergence arises from *Gaia* which, as can be gathered from §A.5, has a policy of registering both extragalactic transients and strong variables (e.g., AGN and eruptive variables) to TNS.

I carried out an analysis of ATs for the sample of ATs with discovery magnitude  $< 17.5$ . There are 1608 such events, of which only 225 are classified. The latter set is composed of 161 SNe, 45 CVs and a smattering of “Galaxy” (which means that the classification spectrum was dominated by galaxy light), “variable stars”, “novae” and “AGN”.

The counts from the reporting agents for the remaining 1383 ATs can be found in Table 5. As expected the leading contributor of bright unclassified ATs is *Gaia*. MASTER also has a similar philosophy as *Gaia*, namely, to report strong variables, eruptive variables and transients to TNS. However, given that ZTF and ATLAS are focused on genuine transients it is rather surprising to find large contributions to this Table from ZTF and ATLAS.

### C. SEDM: AN ULTRA-LOW RESOLUTION SPECTROGRAPH TUNED FOR SN CLASSIFICATION

Traditionally, spectral classification has been done with “Low resolution” optical spectrographs such as the famed Double Beam Spectrograph (DBSP) on the 200-inch telescope or the Double Imaging Spectrograph on the 3.5-m telescope of the Apache Point Observatory. The spectral resolution,  $R = \lambda/\Delta\lambda$ , of such spectrographs is a few thousand. With this resolution it is easy to distinguish active stars (flare stars, RS CVn etc.), cataclysmic variables, supernovae, tidal disruption events and burping AGNs. However, when detectors have read noise (as is still the case with current generation of CCDs) then spectral resolution comes with a cost. The larger the spectral resolution, longer is the minimum exposure time or equivalently one needs a larger telescope (for the same exposure time).

Supernovae dominate the demographics of extragalactic transients. The expansion speeds of supernovae  $v \gtrsim 3,000 \text{ km s}^{-1}$ . Thus a spectral resolution of  $R \approx c/v$  or one hundred is adequate to classify supernovae and tidal disruption events. This resolution is certainly inadequate for spectral classification of stars.

Motivated thus we constructed an *ultra-low* resolution spectrograph with  $R \approx 100$ . SEDM is the sole instrument on the Palomar 60-inch telescope (henceforth, “SEDMv1”). In order to cut down on acquisition time we opted for an integral field unit (IFU) with a wide entrance field-of-view of  $30''$  on the side. Given the low resolution and the

<sup>29</sup> <http://ogle.astrouw.edu.pl/ogle4/transients/>

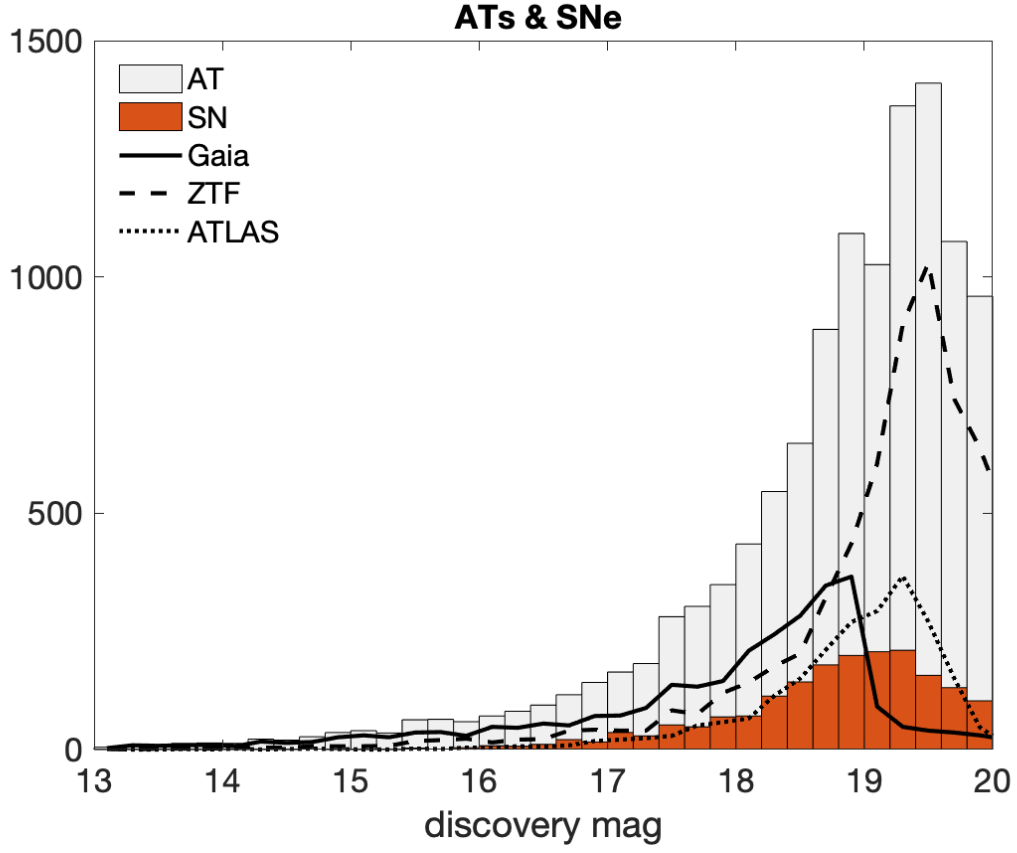
**Table 4.** Histogram of Host Galaxy Catalogs

Galaxy Catalog	$n_g$
SDSS	576
WISE	353
2MASS	339
OGLE	96
GALEX	58
NGC	53
LEDA	47
UGC	45
CGC	34
ESO	29
MCG	19
M31	18
PGC	17
IC	17
KUG	15

NOTE—Column 1 is the entry for galaxy catalogs and  $n_g$  (column 2) is the number of galaxies in that catalog. The histogram has been cut-off at  $n_g < 10$ .

expected high target throughput we called it as the “Spectral Energy Distribution Machine” (SEDM). The hardware and initial performance details can be found in [Blagorodnova et al. \(2018\)](#). Data reduction of IFU data is very tricky and subtle. The details of the data reduction pipeline can be found in [Rigault et al. \(2019\)](#).





**Figure 6.** As in Figure 4 but with an emphasis on the bright end.

**Table 5.** Histogram of Bright ( $< 17.5$  mag) Unclassified ATs

Reporting Group	$n_r$
GaiaAlerts	798
ZTF	331
ATLAS	75
MASTER	70
ASAS-SN	46
uno	8
Pan-STARRS1	7
BraTS	7
ALeRCE	7
XOSS	6
GSNST	6
Gattini	5

NOTE—Column 2 is the number of unclassified bright ( $< 17.5$  mag) ATs reported by group (Column 1). ATs with field 9 (reporting group) are assigned “uno”. Most of them are detections reported by amateur astronomers. The histogram has been cutoff at  $n_r < 5$ .